AIHA SMNR BEST FIT STUDY

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Revision	Date	Prepared by	Reviewed by	Client
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EXECUTIVE SUMMARY

The Alberta Industrial Heartland Association (AIHA) has asked Fluor Canada Ltd. (Fluor) to prepare a report to assist AIHA in evaluating several use case scenarios for the deployment of Small Modular Nuclear Reactors (SMNRs) in the Heartland region.

The SMNR study aims to:

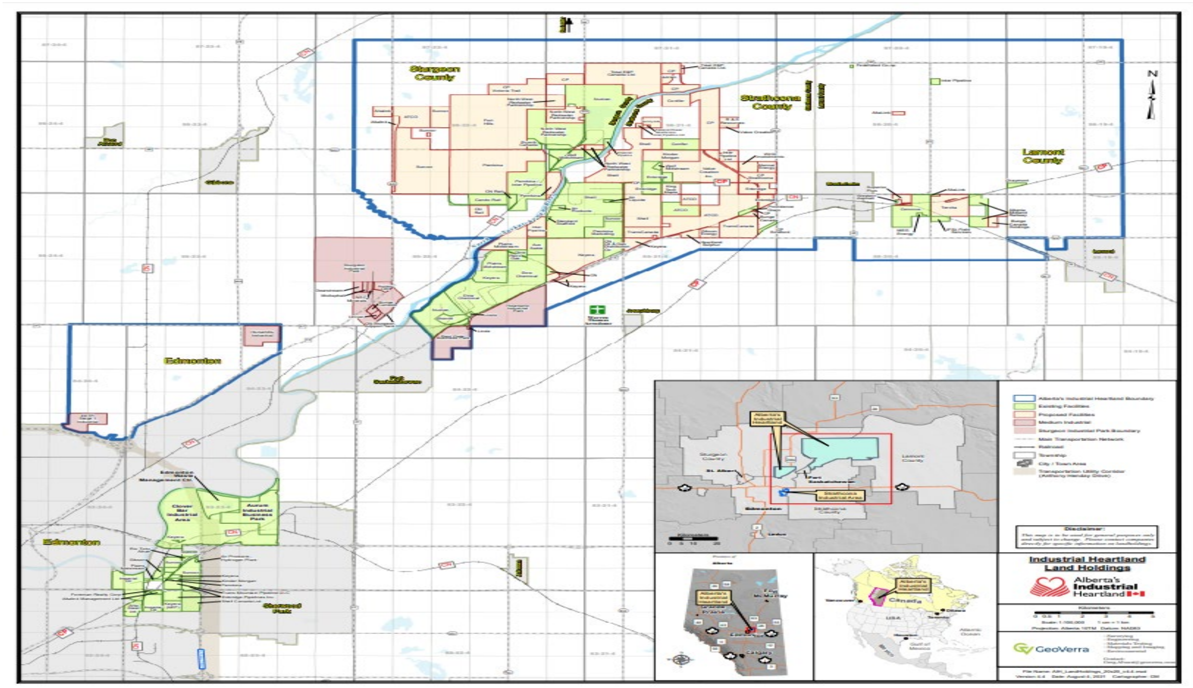
- Conduct high-level evaluations of current SMNR technologies.
- Evaluate the technical and economic opportunities associated with SMNRs for current and future facilities in the Alberta Industrial Heartland (AIH).
- Evaluate the decarbonization opportunities SMNRs can provide for power and steam generation.
- Provide an economic comparison between SMNRs and other mechanisms to achieve Green House Gas (GHG)-reduced steam and power generation.
- Provide a timeline comparison between the for deployment of SMNRs and competing technologies.
- Evaluate deployment scenarios for SMNRs, e.g., larger scale deployment vs. individual smaller scale deployment. Use cases such as power generation, steam generation, district heating, and hydrogen production all to be considered.

THE OPPORTUNITY

The AIH is a designated industrial zone located northeast of Edmonton that is comprised of five municipal partners; the city of Fort Saskatchewan, Lamont County, Strathcona County, Sturgeon County, and the City of Edmonton. The AIH is Canada's largest hydrocarbon processing region and supports several chemical and petrochemical facilities. A map of the region is provided in Figure 1.

The AIHA is committed to establishing a best-in-class regulatory framework to attract new investment, and demonstrating environmental stewardship. The framework shall be consistent with that established that allows recognition as a designated industrial zone within the province of Alberta.

With over $145 billion in planned projects the AIHA is looking to help inform its current and potential members and investors the options available to meet the regulatory Environmental Social and Governance (ESG) mandates as well as individual companies' own corporate ESG commitments.



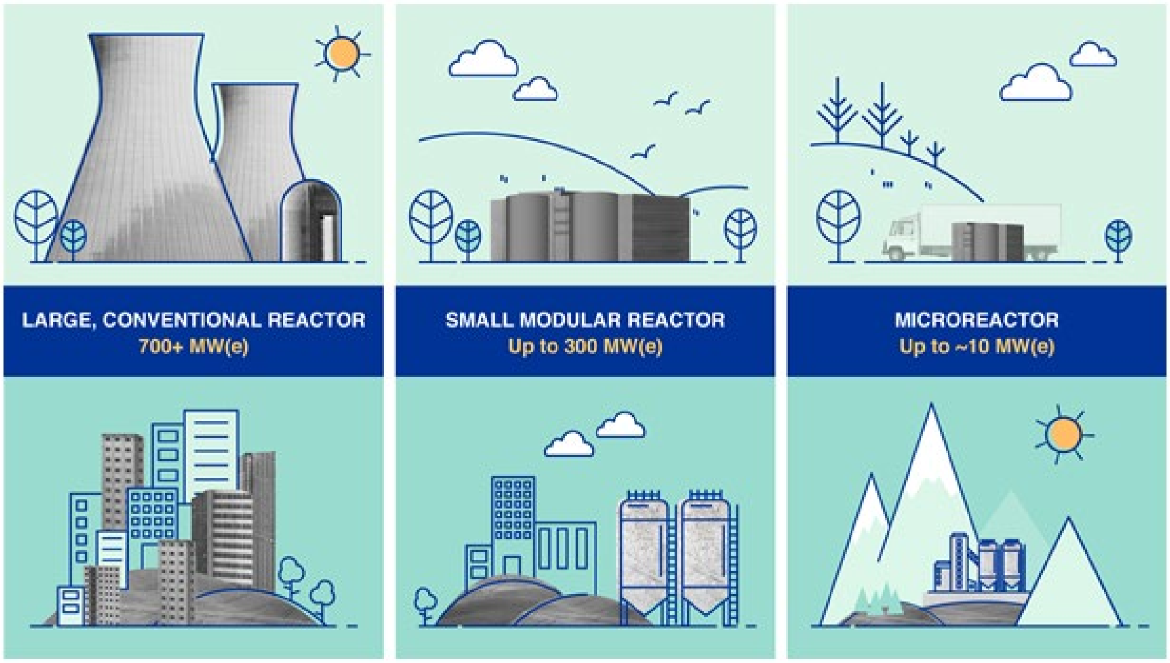
Source https://industrialheartland.com/wp-content/uploads/2022/03/AIH_LandHoldings_v4.4_20x20.pdf

Figure 1. Alberta Heartland Region. *The AIH is Canada's largest hydrocarbon processing region and supports several chemical and petrochemical facilities.*

WHY CONSIDER SMNRs?

SMNRs in Canada have been gaining attention due in large part to Natural Resources Canada's SMNR Action Plan, which brings together a number of key enablers to establish what is being termed a "new nuclear" industry in Canada. Memorandums of Understanding (MOU) between Ontario Power Generation and SaskPower, as well as between Alberta, Saskatchewan, New Brunswick, and Ontario have been developed to explore the deployment of SMNRs. These MOUs have validated SMNRs as a viable part of the generation that will be required for Canada to meet the dual challenge of our 2050 Net Zero commitments while supporting the electrification of our nation.

SMNRs are a step change in nuclear technology as they are passively safe, no longer require large emergency planning zones, and can be effectively close-coupled with industrial facilities. These features present a significant opportunity for steam generation and district heating applications in addition to the generation of electricity. For clusters of industry which require significant baseload generation, SMNRs offer a GHG-reduced manner to achieve this baseload against which renewables can be deployed providing low emission, reliable power.



Source: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

Figure 2. What are SMNRs? *SMNRs are a step change in nuclear technology as they are passively safe, no longer require large emergency planning zones, and can now be effectively close-coupled with industrial facilities.*

FINDINGS

Fluor has considered 10 potential applications where SMNRs could be deployed in the AIH to meet energy demands while reducing GHG emissions. These cases are not meant to represent specific sites in the Heartland area, rather they are representative of opportunities to reduce emissions at the scales noted.

- Case 1: 880 kg/hr H_2 from low temperature electrolyzer
- Case 2: 1,250 kg/hr H_2 from high temperature electrolyzer
- Case 3: 525,000 tpa propylene/polypropylene complex
- Case 4: 1,275,000 tpa ethylene production
- Case 5: 1,750,000 tpa methanol production
- Case 6: 700,000 tpa Ammonia production
- Case 7: 164 MWth (200 building) Commercial district heating
- Case 8: 1,000 MMSCFD natural gas and natural gas liquids (NGL) production
- Case 9: 88 MW simple cycle Power generation
- Case 10: 164 MWth (9,000 to 12,000 homes) Residential district heating

GHG AVOIDANCE

GHG avoidance could be achieved through the introduction of SMNRs to displace current fossil fuel energy sources. In the cases below, SMNRs were considered to displace imported power from the grid, externally generated steam from natural gas, or to produce heat for district heating.

	END-USE CASE	POWER REQUIREMENT	NET GHG EMISSIONS AVOIDED
1	Hydrogen Production via Low Temperature Electrolysis	44 MW_e	0.21 MM tonnes CO_2e/yr
2	Hydrogen Production via High Temperature Electrolysis	44 MW_e plus 11.6 MW_{Th}	0.27 MM tonnes CO_2e/yr
3	Polypropylene Production	102 MW_e plus 153 MW_{Th}	0.60 MM tonnes CO_2e/yr
4	Ethylene Production	55.4 MW_e	0.27 MM tonnes CO_2e/yr
5	Methanol Production	3.1 MW_e	0.015 MM tonnes CO_2e/yr
6	Ammonia Production	11 MW_e	0.053 MM tonnes CO_2e/yr
7	Commercial District Heating	164 MW_{Th} (commercial district heating)	0.13 MM tonnes CO_2e/yr
8	Natural Gas and NGL Production	231 MW_e	1.10 MM tonnes CO_2e/yr
9	Power Generation	88 MW_e	0.37 MM tonnes CO_2e/yr
10	Residential District Heating	164 MW_{Th} (residential district heating)	0.13 MM tonnes CO_2e/yr

SELECTION FROM AVAILABLE SMNR TECHNOLOGIES

An analysis of the available SMNR technologies was conducted to identify reactor designs that could meet the energy requirements presented in the 10 use cases. Starting with the 72 SMNR designs listed by the International Atomic Energy Agency, a technology down-select was applied in two steps. In Step 1, basic filtering was applied to remove technologies that were assessed as not meeting the critical criteria for technology/deployment readiness and regulatory readiness. In Step 2, the power production capacity of the remaining SMNRs were examined for each of the applications.

A total of nine SMNR technologies capable of meeting one or more of the end-use cases emerged from the screening criteria:

- ARC-100
- Moltex
- Terrestrial Energy
- X-energy Xe-100
- NuScale
- Holtec SMR-160
- GE-Hitachi BWRX-300

- USNC-MMR
- Westinghouse eVinci

The nine selected technology designs are currently under review either by the governing regulatory bodies in Canada, the United States, or the United Kingdom. The nine selected SMNR technologies are expected to be ready for deployment by 2035; additionally, they each have projects currently underway. All the final selected technologies meet the above criteria; however, this list does not constitute an endorsement for or against any specific technology provided.

CHALLENGES

Some risks associated with the first-of-a-kind development (FOAK) for SMNRs include:

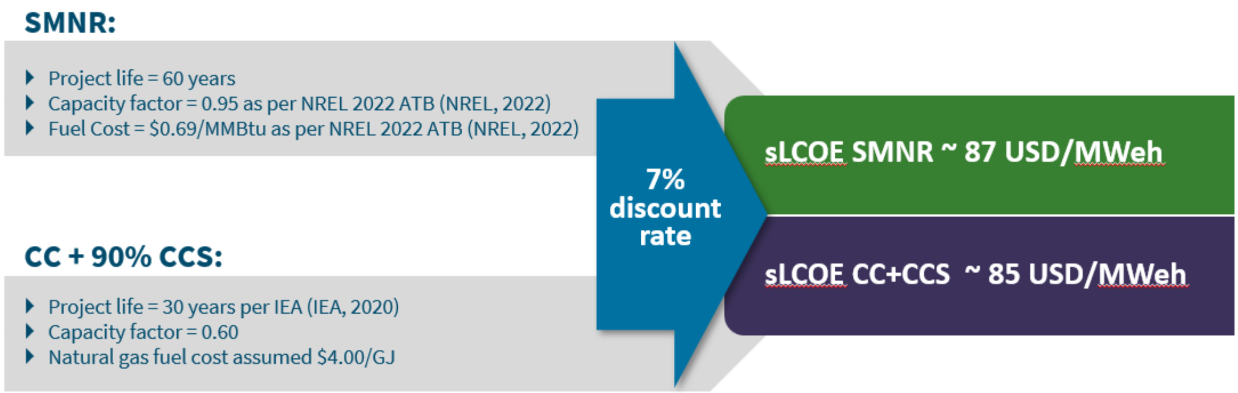
- **Lack of operating experience.** Most proposed designs have novel operational requirements and therefore there is a lack of available personnel with operating experience.
- **Supply chain uncertainty.** The supply chain required to producing multiple modules has not yet been demonstrated.
- **Cost uncertainty.** There is a lack of precision in SMNR cost estimates due to various factors such as inflation, capital cost, uncertainty with FOAK designs.
- **Regulatory uncertainty**. Many of the SMNR designs have not been fully evaluated or licensed by regulators. Reduced physical security requirements claimed by SMNR vendors have not been approved by regulators.
- **Fuel unavailability**. SMNR designs which propose the use of High Assay Low Enriched Fuel (HALEU) currently face supply challenges. As of the of writing of this report, there are no commercially available sources HALEU in any OECD country. In addition, HALEU-based designs (as well as some other designs which use variants of Low Enriched Fuel (LEU)), further fuel development and qualification may be required.

ECONOMIC VIABILITY

It is recognized there is uncertainty in the current cost of SMNRs. Levelized costs for electricity and steam were estimated using a simplified costing model and best available open-source information.

One of the advantages of nuclear technologies is their Levelized Costs of Electricity (LCOE) are not as impacted due to variations in the cost of fossil fuels. There are additional costs to the LCOE for an SMNR with cogeneration of heat and steam due to the costs of the secondary exchangers and integration with the end-users. These secondary heat exchanger and integration costs are not yet well defined by SMNR technology vendors and are highly specific to the process technology receiving the heat or steam. For the purposes of this study these costs are not considered.

Using overnight, O&M, and heat rates reported by EIA (2022) for both an SMNR and a natural gas fired combined cycle (with carbon-capture), the simplified LCOE indicated that SMNRs can be cost-competitive with fossil fuels, with an estimated LCOE of approximately \$87 USD per MW_eh.



For comparison, the National Association of Regulatory Utility Commissioners (NARUC) reported a range of LCOE values ranging between $87 and 131 USD/MW$_e$h (NARUC, 2022) for SMNRs. Assuming a nominal thermal efficiency of 30 percent (some SMNR may have higher efficiencies) this range of costs translates to a cost of steam in the range of $5.5 to 8.3 USD/1,000-lb. This assessment did not adjust the capital cost of the SMNR by removing the steam-turbine for power production. NREL estimated the cost of steam from natural gas ($4 USD/GJ) without carbon-capture as ~ $7 USD/1000-lb, and the cost of steam from nuclear as ~$9 USD/1,000-lb for a nuclear cost of $75 USD/MW$_e$ (NREL, 2018). The NREL study does not appear to consider the costs of carbon-capture from the flue gasses when producing steam via natural gas. A rough estimate of the additional cost of carbon-capture for steam is approximately $5 to $6 USD/1,000-lb of steam, which will further disadvantage steam production via natural gas.

When interpreting cost data from multiple studies the user should proceed with caution because the underlying assumptions are not always fully presented and therefore the numbers may contain inconsistencies. The above costs should be considered as preliminary. The results indicate that SMNR can be competitive with natural gas to produce steam or electricity and SMNRs are further advantaged by high natural gas costs. However, the costs should be reassessed as the vendors further develop their SMNR technologies and equipment costs.